ACOUSTIC MICROSCOPY WITH MIXED MODE TRANSDUCERS

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INTRODUCTION

Acoustic microscopes have become important NDE tools in recent years. For accurate and quantitative characterization, it is desirable to have a system capable of dealing with a wide variety of materials, to evaluate both bulk and surface wave properties, and to detect surface damage, subsurface cracks, bulk defects, etc. For this purpose, we have built a new and versatile acoustic microscope which measures both amplitude and phase in the frequency range of 1-200 MHz with selectable operation modes with longitudinal waves, shear waves, or both. The wide frequency range allows us to evaluate a variety of materials. The selectable operation modes enable us to measure different properties of materials and to detect different types of defects.

ELECTRONICS

The new amplitude-phase acoustic microscope operates in the 1-200 MHz frequency range. A block diagram of the RF electronic hardware is shown in Fig. 1. The RF electronics generates two 300 MHz cw signals whose phases are digitally controlled with respect to each other. The two signals are mixed with the output of a synthesizer (1 MHz-1 GHz) to produce information and reference signals at the desired operating frequency by simply varying the frequency of the synthesizer. A tone burst is derived from the information signal and is used to excite the transducer. The return signal from the sample is then mixed with the reference signal and the product is lowpass filtered, sampled, and digitized. For a measurement at one spot, the information signal is phase shifted with respect to the reference signal by one tenth of $360°$ ten times; the corresponding digitized results vary sinusoidally with the phase shifts. Simple signal processing of these ten data points is used to extract the amplitude and phase of the first harmonic and to remove, at the same time, DC and higher order harmonic components introduced by the nonlinearities of the system. The amplitude and phase are measured with 0.2% and $0.2°$ accuracy, respectively, at 120 MHz, which corresponds to the electronic noise limit of the system. The mechanical noise introduced while scanning reduces the accuracy to 1% for amplitude and $4°$ for phase at the same frequency of 120 MHz.

MIXED-MODE TRANSDUCER

Conventional acoustic microscopes use longitudinal wave based transducers. Longitudinal transducers on buffer rods are good for imaging surface structures and bulk defects, while shear wave transducers on buffer rods are much more efficient for surface

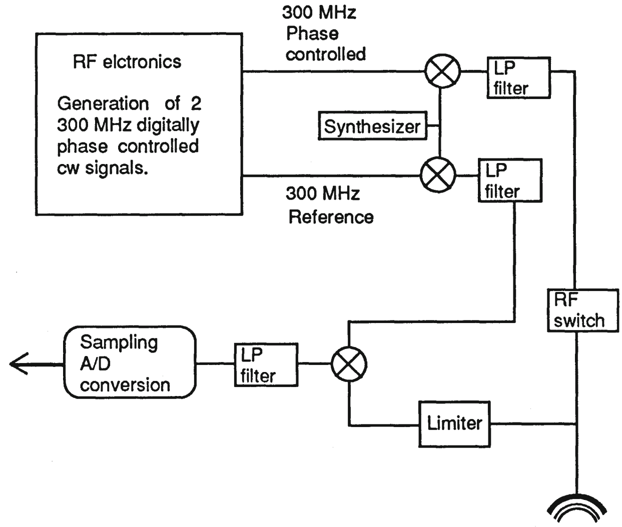


Fig. 1. Block diagram of electronics for amplitude-phase microscope operating at 1-200 MHz .

wave excitation. Therefore, shear wave transducers provide better spatial resolution in applications related to surface wave properties, such as subsurface crack imaging or surface wave velocity mapping [1,2].

Surface wave velocity mapping is based on phase measurement. For accurate phase variation measurements with a high spatial resolution, it is essential to generate two well-separated beams, the on-axis ray path and the Rayleigh (surface wave) ray path, with only a couple of wavelengths of defocusing. The longitudinal transducer lens system generates both beams, which can be separated only when the amount of defocusing is over 30 wavelengths in water, thus limiting the spatial resolution. The shear wave transducer generates a strong surface wave beam with no on-axis beam because the shear wave propagating in the lens cannot be converted into a longitudinal wave in the water at normal incidence. Therefore, the ideal transducer would be a mixed-mode transducer which generates both longitudinal and shear waves simultaneously and efficiently.

As shown in Fig. 2, the surface of an object can be placed between the foci corresponding to the longitudinal and shear waves in the buffer rod. These two focal distances are given by:

$$f_{0L} = r/(1-v_w/v_L) \qquad (1)$$

$$f_{0S} = r/(1 - v_w/v_S) \qquad (2)$$

where r is the radius of curvature of the lens, v_W is the longitudinal velocity of water, and v_L and v_S are the longitudinal and shear velocities of the lens material, respectively. The longitudinal focal distance is shorter than the shear focal distance because the longitudinal wave velocity is about twice as large as the shear wave velocity in most buffer rods.

In this position, the surface waves excited on a sample are due to the shear wave in the buffer rod only, as the surface waves excited by the longitudinal wave propagate away from the lens and are not received by the transducer. The on-axis signal due to the longitudinal wave is used as a reference signal for the phase measurement of the shear wave.

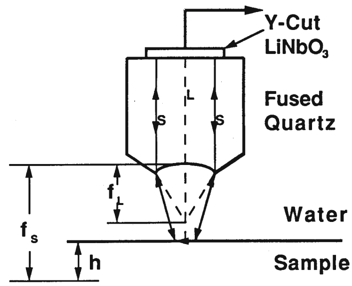
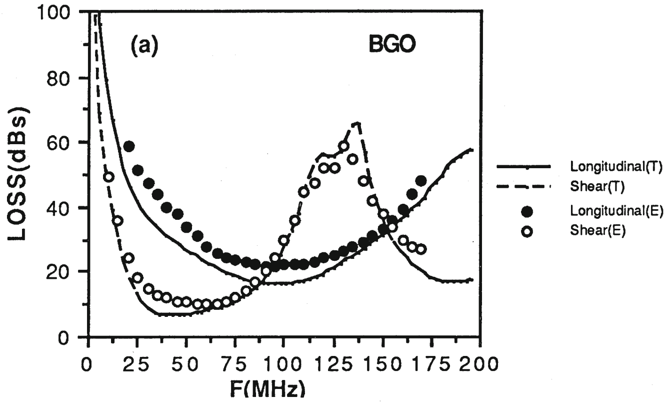


Fig. 2. Mixed-mode transducer-lens configuration for surface wave velocity perturbation measurement.



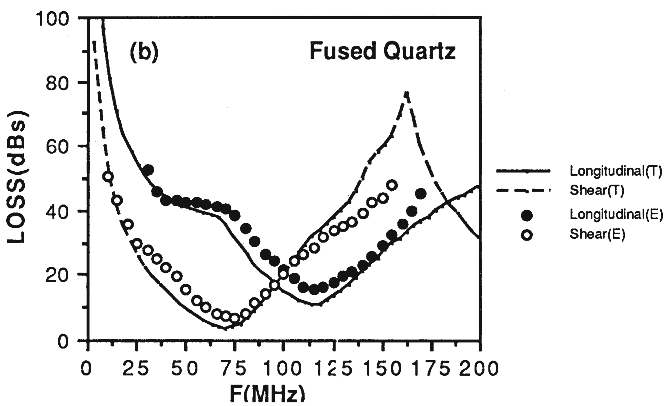


Fig. 3. Comparison of experiment (E) with theory (T) of round-trip insertion loss for 2 mm (diameter) x 25 μm Y-cut $LiNbO_3$ transducers on [110] $Bi_{12}GeO$ (a) and fused quartz (b).

These two beams are separated temporally because their propagation times in the buffer rod are significantly different. The on-axis beam is used as a reference of the phase measurement which makes it possible to eliminate the effects of sample alignment and height variations, as well as the temperature variation in the lens and water path. Therefore, when the transducer is scanned over a sample, the measured phase perturbation $\Delta\phi$ can be written as [3]:

$$\Delta\phi = 2\pi f \, (2h \tan \theta_R / v_R) \, (\Delta v_R / v_R) \tag{3}$$

where ϕ is the relative phase between the two beams stated above, f is the operation frequency, h is the defocusing distance of the shear mode, θ_R is the Rayleigh critical angle and v_R is the Rayleigh wave velocity of the object under investigation.

Since the phase perturbation $\Delta\phi$ is directly proportional to the surface wave velocity perturbation Δv_R , an accurate phase measurement with high spatial resolution is of significant importance. In other words, the proper design of the mixed-mode transducer is essential for the applications related to surface wave velocity mapping.

It is well known that piezoelectric single crystals or ceramics with properly selected orientations can generate both longitudinal and shear waves simultaneously [4,5]. In order to design a mixed-mode transducer with high efficiency and broad bandwidth for both the longitudinal and shear wave modes, we have developed a theory to design mixed-mode transducers [6]. Several Y-cut lithium niobate ($LiNbO_3$) transducers have been made on both [110] single-crystal bismuth germanium oxide ($Bi_{12}GeO_{20}$) and fused quartz, and have operated around a frequency of 100 MHz . As shown in Fig. 3, the experimental data of round-trip insertion loss for both the longitudinal and shear modes of the Y-cut $LiNbO_3$ transducers on both [110] $Bi_{12}GeO_{20}$ and fused quartz agree with the theory very well. Ref. 6 contains the details of the theoretical considerations for designing mixed-mode transducers, along with measurement and manufacturing details.

APPLICATIONS

The new phase and amplitude acoustic microscope can be used in many different NDE applications. For instance, bulk defect imaging of lossy materials or at deep locations within a sample can be done at low frequency (as low as a couple of MHz), and small surface features can be imaged at frequencies between 100 to 200 MHz with longitudinal transducers. Subsurface cracks can be imaged with comparable spatial resolution to surface imaging when operated in shear mode. Also, the surface wave velocity mapping can be obtained with high accuracy and good resolution with mixed-mode transducers.

Figure 4 shows amplitude and phase images of the leads of an IC chip in an epoxy package. The leads are 1.5 mm below the surface. A PZT-5H longitudinal transducer on a fused quartz buffer rod with an F2 lens is used for this application. The focus of the longitudinal wave transmitted into the sample is placed at the plane of the IC. The signal reflected from the rough epoxy surface has been gated out for best imaging results of the leads. Since the epoxy is very lossy, the operation frequency was chosen to be 15 MHz , which gave us an acceptable compromise between spatial resolution and sensitivity. We see that the images are of excellent quality and indicate that, for the samples tested, there are no air bubbles around the leads.

Figure 5 is a set of amplitude images of a surface crack on a silicon nitride (Si_3N_4) ball bearing. In this test, a mixed-mode Y-cut lithium niobate ($LiNbO_3$) transducer on fused quartz was used, and only the shear mode was chosen for efficient surface wave excitation. The transducer is operated at 100 MHz and the F-number of the lens for the shear mode is 1. When the acoustic beam is focused on the surface (Z = 0), we obtain a surface damage image which is not very clear. With proper defocusing, around 50 mm (3-4 wavelengths in water), we obtain the best image of the cracks.

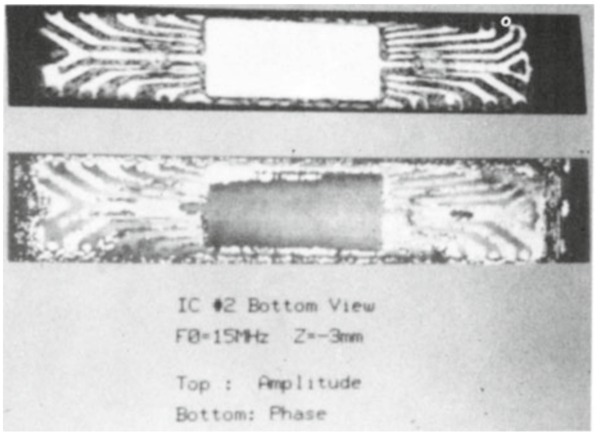


Fig. 4. Amplitude and phase images of the leads of an IC chip in epoxy package. Transducer: $LiNbO_3$ longitudinal transducer. Lens: fused quartz, F2. Operating frequency: 15 MHz. Defocusing amount: 3 mm (which corresponds to focusing on the leads).

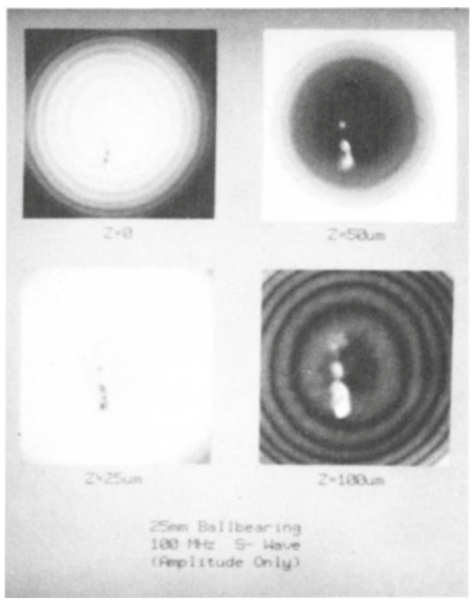
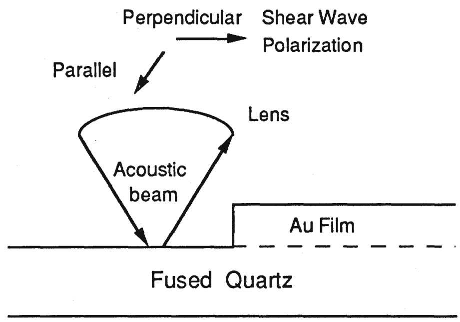


Fig. 5. Amplitude-only images of a subsurface crack on a Si_3N_4 ball bearing. Transducer: Y-cut $LiNbO_3$ transducer; shear mode is chosen for the imaging. Lens: fused quartz, F1. Operating frequency: 100 MHz. Defocusing amount: 0, 25 µm, 50 µm, and 100 µm, as shown in the picture.

Figure 6 shows the phase variation obtained when the transducer is scanned over a thin gold film deposited on a quartz substrate. The same mixed-mode transducer as in Fig. 5, operating at 100 MHz, is used with a reference beam provided by the longitudinal mode. A signal beam is provided by the shear mode with 60 µm (4 λ in water) defocusing. Since the signal beam illuminating the sample is converted from the shear mode, it is anisotropic. Therefore, the spatial resolution varies with the orientation of the transducer. As expected, the spatial resolution of the transducer-lens system with the polarization parallel to the edge of the gold film is much better than that with perpendicular polarization (30 μm versus 55 μm was measured). The thickness of the gold film was measured by an alpha step profilometer to be 1500±135 Å, which corresponds to the phase variation of 32.8°±3°, according to Eq. (3) and reference [7]. The experimental results of phase variation for both the parallel and perpendicular orientations of the transducer are 33°±3°, which shows excellent agreement with the theoretical prediction.



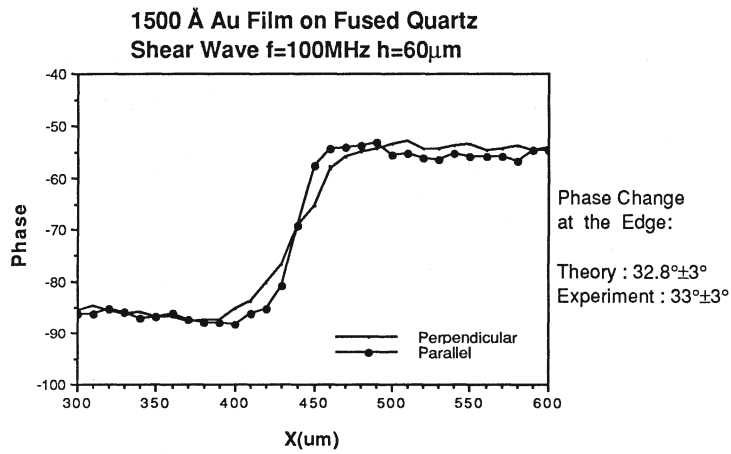


Fig. 6. Measurement of phase perturbation due to gold film on fused quartz. Transducer: mixed-mode Y-cut $LiNbO_3$ transducer. Lens: fused quartz, F1. Operating frequency: 100 MHz. Defocusing amount: 60 μm.

CONCLUSION

The new amplitude-phase acoustic microscope is a versatile system. It operates in a wide frequency range of 1-200 MHz with selection of longitudinal, shear, and mixed-modes. This enables it to be used in many NDE applications for different kinds of materials. Except for the application examples that we have presented in this paper, this system can also be applied for residual stress and anisotropy mapping with high accuracy and good spatial resolution.

ACKNOWLEDGMENT

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